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OCEAN SURFACE WAVES PRODUCED BY SOME RECENT HURRICANES

ARTHUR PORE

U. S. Weather Bureau, Washington, D. C.

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ABSTRACT

Composite charts of surface wave conditions for several recent hurricanes are presented. The data suggest that the highest average wave height occurs in the right front quadrant as often as in the right rear quadrant. Tide records during two hurricanes when long swells were arriving at the coast are examined for an effect of swell on the tide level.

1. INTRODUCTION

Among the elements of a hurricane, breaking waves are the most destructive. They often demolish boats, docks, buildings, and other private and public property. Such waves are more destructive when superimposed on an abnormally high tide. Forty to forty-five foot waves were reported by Coast Guard stations in New England during hurricanes Carol and Edna of 1954. More recently, hurricane Greta of November 1956, which passed several hundred miles north of Puerto Rico, produced the highest seas in the memories of the inhabitants of the southern and western coasts of Puerto Rico. Thirty-foot swells were reported crashing on the reefs along the southern and western shores and 16- to 20-foot waves were observed along the northern shore after the storm passed north of the island.

The purpose of this study is to present a descriptive view of surface wave conditions in some recent hurricanes with emphasis on two aspects: (1) areal distribution of wave conditions, and (2) propagation of swell and its effect on tide level.

2. RELATED STUDIES

Cline [3] in 1920 concluded that the highest waves and swell are produced in the right rear quadrant of the hurricane and that these waves advance through the smaller waves of the forward portion of the storm, keeping the direction of the motion at the time of wave generation. The basis for this conclusion is that the winds on the right side of the storm blow in about the same direction as the storm movement, thereby permitting longer fetches, longer duration times, and higher wind speeds to exist in the right quadrants of the storm.

Tannehill [7] prepared a composite chart from twelve synoptic maps showing observations of wind and swell directions for the Atlantic hurricane of August 1935. The observations showed that the direction of the swell deviated to the right of the wind. The largest average deviation was in the left rear quadrant, whereas the smallest average deviation occurred in the right rear quadrant. The two front quadrants had intermediate average deviations of about equal magnitude. It was concluded that the deviations of the swell from the wind in the various parts of the hurricane are dependent on the movement of the storm. He also found that to the rear of the storm path there is a line of discontinuity in the direction of swell.

The Scripps wave forecasting theory was adapted [8] to the estimation of waves in hurricanes by dividing the storm into sectors with constant wind direction in each sector and with wind speed dependent on the distance from the storm center.

Arakawa and Suda [1] have presented composite charts of wind speed and direction, state of the sea, and swell for the typhoon of September 26, 1935, over the North

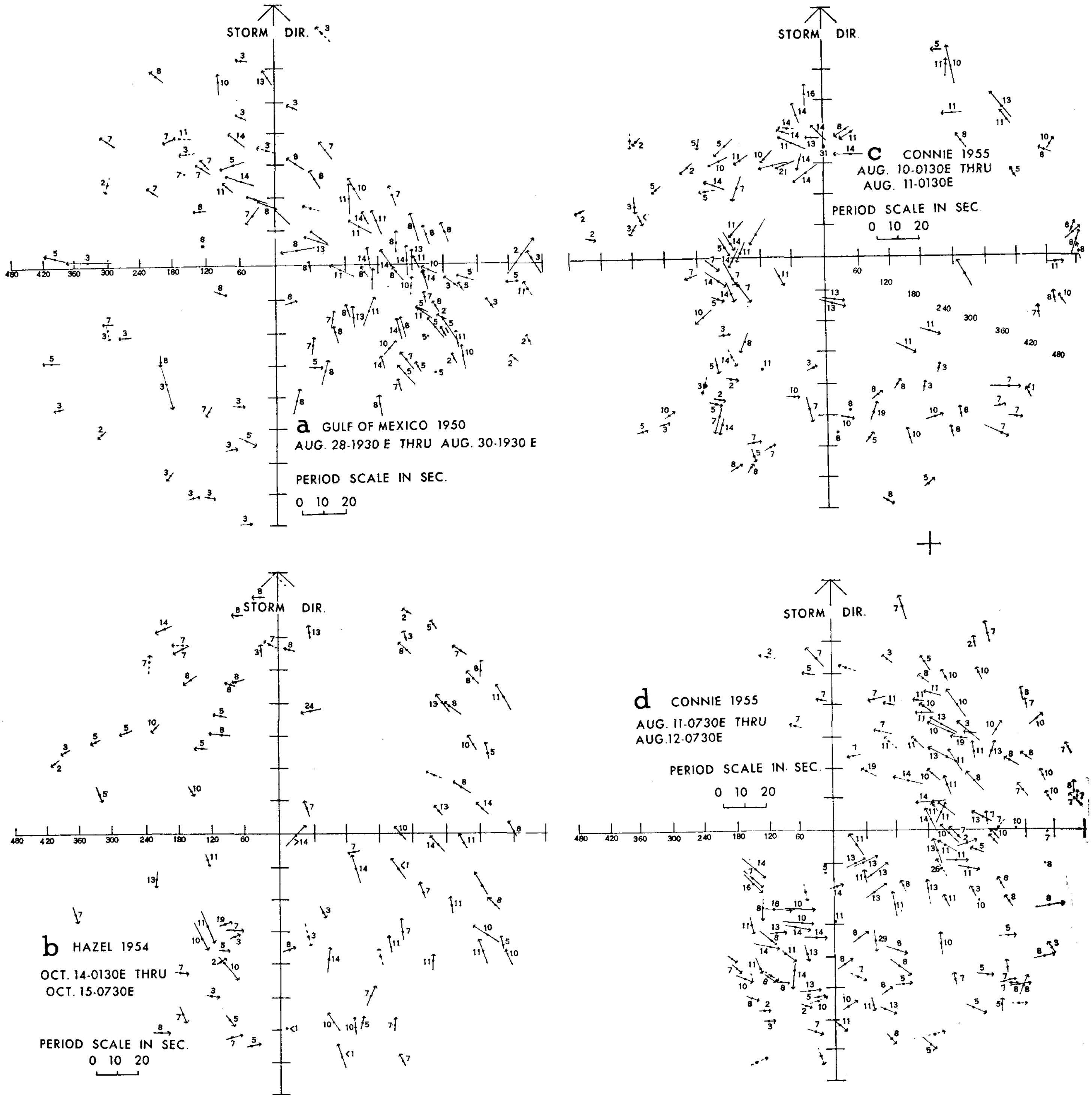

FIGURE 1.—Composite wave charts. The wave height in feet is plotted beside the arrow indicating direction from which the waves came. The length of the arrow is proportional to the wave period. Dashed arrow indicates unknown period. Distances are marked along the radii at intervals of 60 nautical miles.

Pacific just east of Japan. This storm passed over a main squadron of the Japanese Navy and consequently the wave conditions within the storm were relatively well recorded. They found that the highest waves occurred in the right rear quadrant. Their composite chart of swell showed that among the high swell (greater than 12 feet), the longest occurred in the right rear quadrant.

Arakawa [2] has pointed out that in a limited area of the right rear quadrant the directions of the swell deviate to the left of the wind directions, whereas they deviate to the right within most of the storm area. In the limited area where the directions of the swell deviate to the left of the wind directions, pyramidal waves are produced by the interaction of the swell and the wind waves.

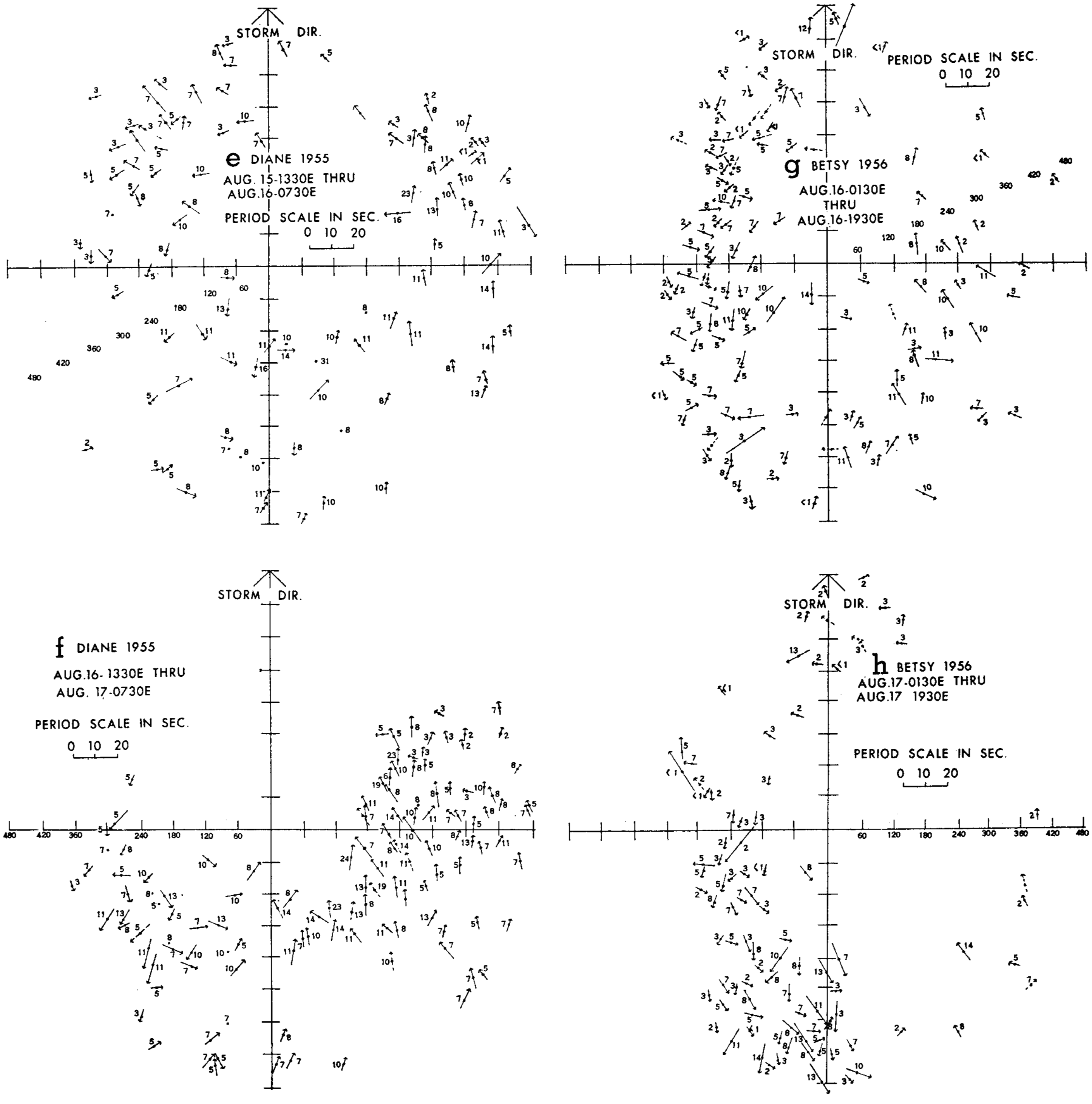

FIGURE 1—Continued.

3. AREAL DISTRIBUTION OF WAVE CONDITIONS

Synoptic charts of ship observations have been plotted to study the wave conditions of some recent hurricanes. The synoptic reports and the ships' records of weather observations include observations of wave direction, wave height, and wave period. No distinction is made in these reports and records between sea (waves produced by the local wind) and swell (waves which have propagated out of the generating area). Certainly, wave direction, height, and period are among the more difficult parameters to observe accurately. The subjectivity of visual wave observations has been pointed out by Pierson, Neumann, and James [5] who state, "The procedure is often for some observer to look out over the sea surface and make a

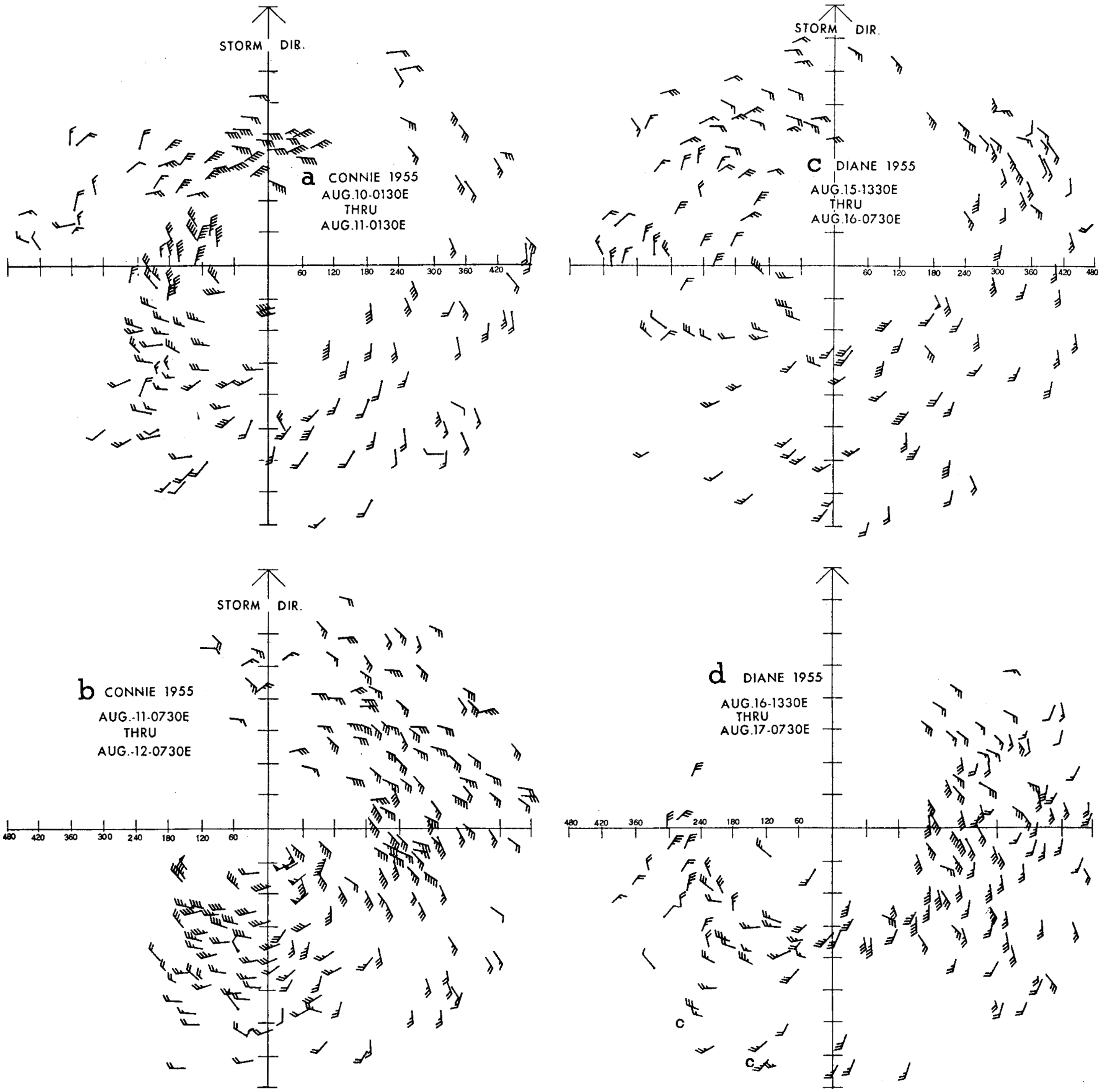

FIGURE 2.—Composite wind charts for hurricanes Connie and Diane, 1955. Wind speeds are plotted in Beaufort force. Distances are marked along the radii at intervals of 60 nautical miles. Calm is indicated by C.

quick guess as to the wave height." The subjectivity involved in making them must be kept in mind when working with wave observations and some discrepancies are to be expected.

Composite charts of wave conditions out to 480 nautical miles from the centers of the storms were prepared by aligning the direction of motion of the storm on the synoptic charts and keeping the location of the storm center constant on the composite charts. The composite charts (fig. 1a-h) show the directions from which the waves came, the wave heights in feet, and the periods in seconds. Wave observations usually are not available near storm centers and therefore the highest waves are probably not indicated on the composite charts. Composite wind charts (fig. 2a-d) were prepared in the same manner for hurricanes Connie and Diane of 1955.

The average wave heights, wave periods, and number of observations considered in each quadrant of several

TABLE 1.—*Average wave heights and periods in the different quadrants in some recent hurricanes. All times in EST*

	Average wave height								Average wave period							
	Right front		Right rear		Left front		Left rear		Right front		Right rear		Left front		Left rear	
	ft.	*ob.*	*ft.*	*ob.*	*ft.*	*ob.*	*ft.*	*ob.*	*sec.*	*ob.*	*sec.*	*ob.*	*sec.*	*ob.*	*sec.*	*ob.*
GULF OF MEXICO, 1950																
1930, Aug. 28–1930, Aug. 30	9.0	24	7.4	45	7.1	26	4.1	17	11.0	25	8.0	48	8.8	23	6.6	16
HAZEL, 1954																
0130, Oct. 14–0730, Oct. 15	9.1	21	8.0	29	6.6	21	7.6	18	7.9	21	9.1	28	6.2	18	7.9	18
CONNIE, 1955																
0130, Aug. 10–0730, Aug. 12	9.6	72	8.9	84	8.5	35	8.5	62	8.5	69	8.3	79	8.6	35	8.2	60
0130, Aug. 10–0130, Aug. 11	10.4	18	8.2	28	9.0	30	7.4	32	9.2	17	7.7	27	8.8	31	7.7	30
0730, Aug. 11–0730, Aug. 12	9.3	54	9.2	56	5.2	5	9.6	30	8.3	52	8.6	52	7.3	4	8.8	30
DIANE, 1955																
1330, Aug. 15–0730, Aug. 17	7.2	67	10.0	70	5.6	36	7.7	59	7.4	68	7.9	64	7.5	36	7.7	52
1330, Aug. 15–0730, Aug. 16	7.3	28	10.7	23	5.6	33	8.2	21	7.6	29	7.2	21	7.5	33	7.1	17
1330, Aug. 16–0730, Aug. 17	7.2	39	9.7	47	5.0	3	7.5	38	7.2	39	8.3	43	7.7	3	8.0	35
JANET, 1955																
0130, Sept. 23–0130, Sept. 28	5.0	32	6.1	49	5.0	32	3.0	31	6.8	28	6.9	49	6.8	29	6.2	23
BETSY, 1956																
0130, Aug. 16–1930, Aug. 17	3.6	19	6.4	43	4.1	58	5.5	92	6.8	19	7.4	42	6.3	54	7.4	91
0130, Aug. 16–1930, Aug. 16	4.3	12	6.4	28	4.5	41	5.3	42	7.7	13	7.1	28	6.0	38	7.0	42
0130, Aug. 17–1930, Aug. 17	2.3	7	6.3	15	3.2	17	5.6	50	5.0	6	8.0	14	7.1	16	7.8	49

storms are contained in table 1. The average wave heights determined are somewhat less than one usually thinks of as being present in the vicinity of a hurricane. However, these averages are based on reports out to a distance of 480 miles from the storm center. Also, there is a definite absence of data on the highest waves which would occur close to the storm center. The wave height averages (table 1) should be considered as being averages over the distance from 60 to 480 miles from the storm centers.

Hurricane Connie of August 1955 progressed slowly off the Carolinas, and ten synoptic wave charts were plotted for the period when the storm was centered between latitudes 30° and 35° N. and longitudes 75° and 77° W. The right front quadrant had the highest average wave height, 9.6 feet. The wave pattern of this storm seems unusual in that the average wave heights in the left quadrants were nearly as great as those of the right quadrants, being 8.5 feet in the left front and left rear quadrants, and the average height in the right rear quadrant was 8.9 feet. The relatively symmetrical pattern of wave heights about Connie was probably due to its slow forward speed of 5 to 8 knots, which would tend to reduce the differences between fetches, duration times, and wind speeds on the two sides of the hurricane.

The synoptic wave charts for Connie were divided into two groups to determine if the average wave heights in the various quadrants were relatively consistent with time or were rapidly changing. The first group was from 0130 EST August 10 through 0130 EST August 11, and the second from 0730 EST August 11 through 0730 EST August 12. The average wave heights as indicated in table 1 for these two periods were not very different, suggesting that the wave height conditions did not change considerably from one day to the next. The value of 5.2 feet for the left front quadrant for the second period is not significant, being based on only five observations.

The pattern of waves produced by hurricane Diane conforms more closely to the classical pattern. The wave conditions for the last two days that the path was over the ocean were examined. In this storm the highest average wave height was 10.0 feet in the right rear quadrant. Again the observations were divided into two groups and the average heights and periods were determined (table 1). It was found, as with Connie, that the average wave heights did not change materially over the time interval involved.

The tabulations of table 1 show that the wave heights in half the storms considered were higher in the right rear quadrant, as usually stated in the literature, whereas the others had their highest average heights in the right front quadrant.

The average wave periods of the quadrants of the storms considered are also included in table 1. At first it was expected that the average of the periods would be higher in the right quadrants of the storms, because of higher wind speeds and longer fetches and duration times of the right quadrants. The average periods were not much different in the various quadrants, usually being between 6 and 9 seconds. However, the Gulf hurricane of 1950 had the highest average period, 11 seconds, in the right front quadrant.

Graphs of wave height and period against distance from the storm center were plotted for several storms and showed little variation of height and period with distance. Although the storms considered were not stationary, the small variations of wave heights and period with distance from the center agree qualitatively with the results for a stationary storm given in [8]. In that study the constancy of height and period with distance are explained by the fact that the decrease in wind velocity with increasing distance is nearly compensated for by the increase in fetch.

4. HURRICANE SWELL AND ITS EFFECT ON TIDE LEVEL

Often a gradual rise of water level is observed at coastal

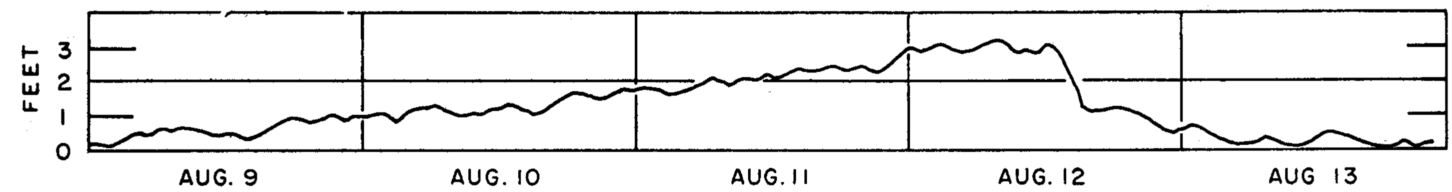

FIGURE 3.—Abnormal tide (difference between observed and predicted tide), Morehead City, N. C., hurricane Connie, 1955.

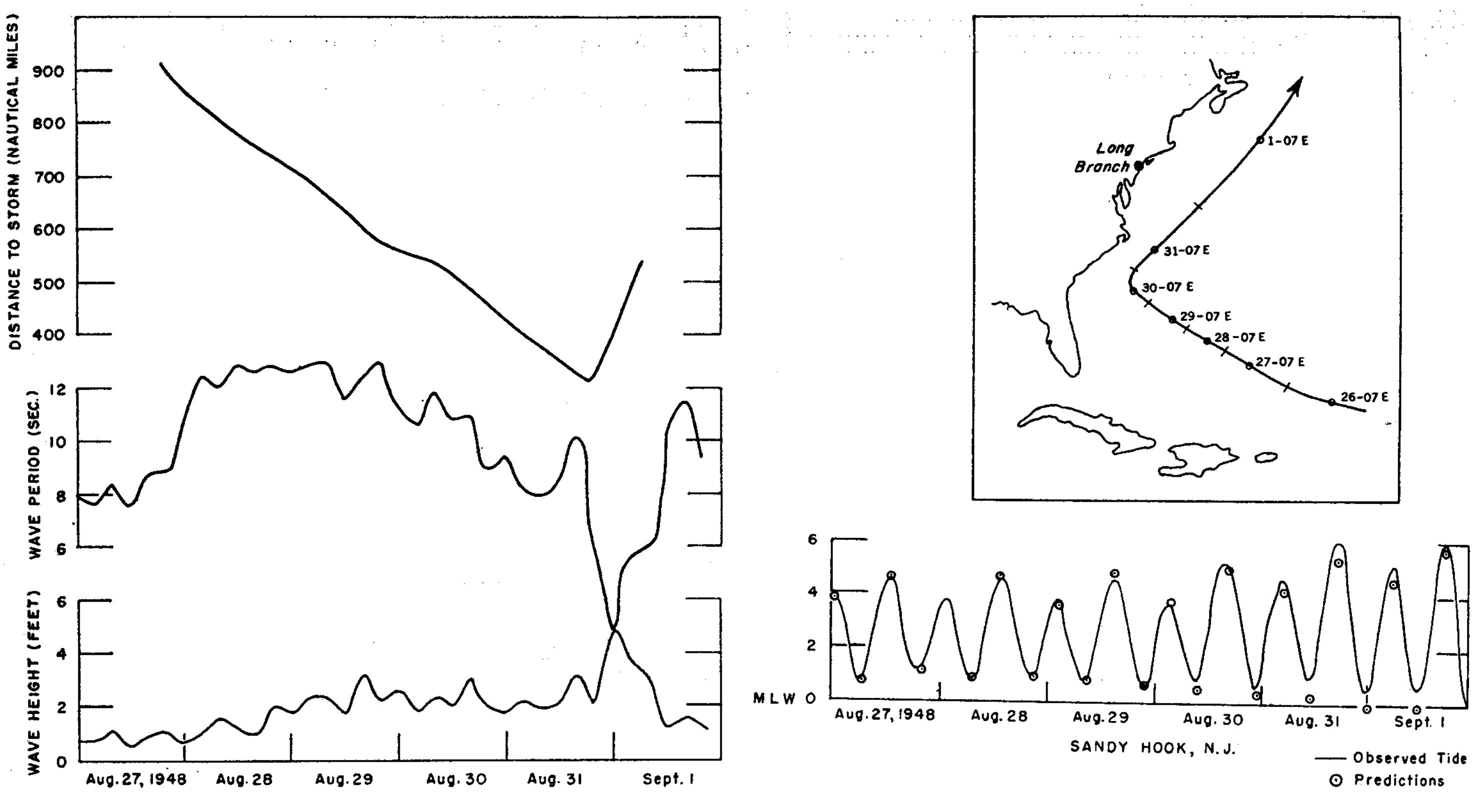

FIGURE 4.—Significant wave heights and periods recorded at Long Branch, N. J., by the Beach Erosion Board during a hurricane in August 1948. Observed tide curve and predictions of high and low tide are for Sandy Hook, N. J.

stations long in advance of the landfall of a hurricane (Redfield and Miller [6], Willett [9]). Cline [3] has attributed the rise in sea level to the transport of water by swells which are generated within a hurricane and propagate out in advance of the storm. Figure 3 shows the difference between the actual water level and the normal water level at Morehead City, N. C., during hurricane Connie of 1955. In this case the abnormal tide began to build up on August 9, three days before the storm came inland. Figure 4 shows the heights and periods of the significant waves, as recorded at Long Branch, N. J., by a Beach Erosion Board wave recorder, and the distance of the storm center during an Atlantic hurricane of August 1948. The curves show increases in significant height and period while the storm was quite distant. The tide record and the tide predictions for Sandy Hook, N. J., are also presented in figure 4. Practically no abnormality occurred in the observed tide during the time that the long-period waves were recorded.

The heights and periods of the significant waves were recorded by the Beach Erosion Board at Melbourne Beach, Fla., during the period of an Atlantic hurricane in September 1951 and are shown in figure 5. The periods of the significant waves were considered as being a measure of the group velocity of the swell propagating from the storm. The group velocity is given by $C_g=1.52T$, where C_g is the group velocity in knots, and T is the wave period in seconds. According to Deacon [4] the speed with which waves advance through an ocean is within 5 percent of the theoretical group velocity as specified by the wave period. This estimate of wave velocity must be somewhat approximate when based on the significant wave period as it underestimates the velocity of the longer waves and overestimates the velocity of the shorter waves.

The distance to the storm at 4-hour intervals was measured and the travel times of all possible waves (considering the range of observed significant periods) were computed (time=distance/group velocity). Comparison was made between the observed wave velocities (based on the observed periods) and the computed wave velocities which would be necessary for waves of a particular period

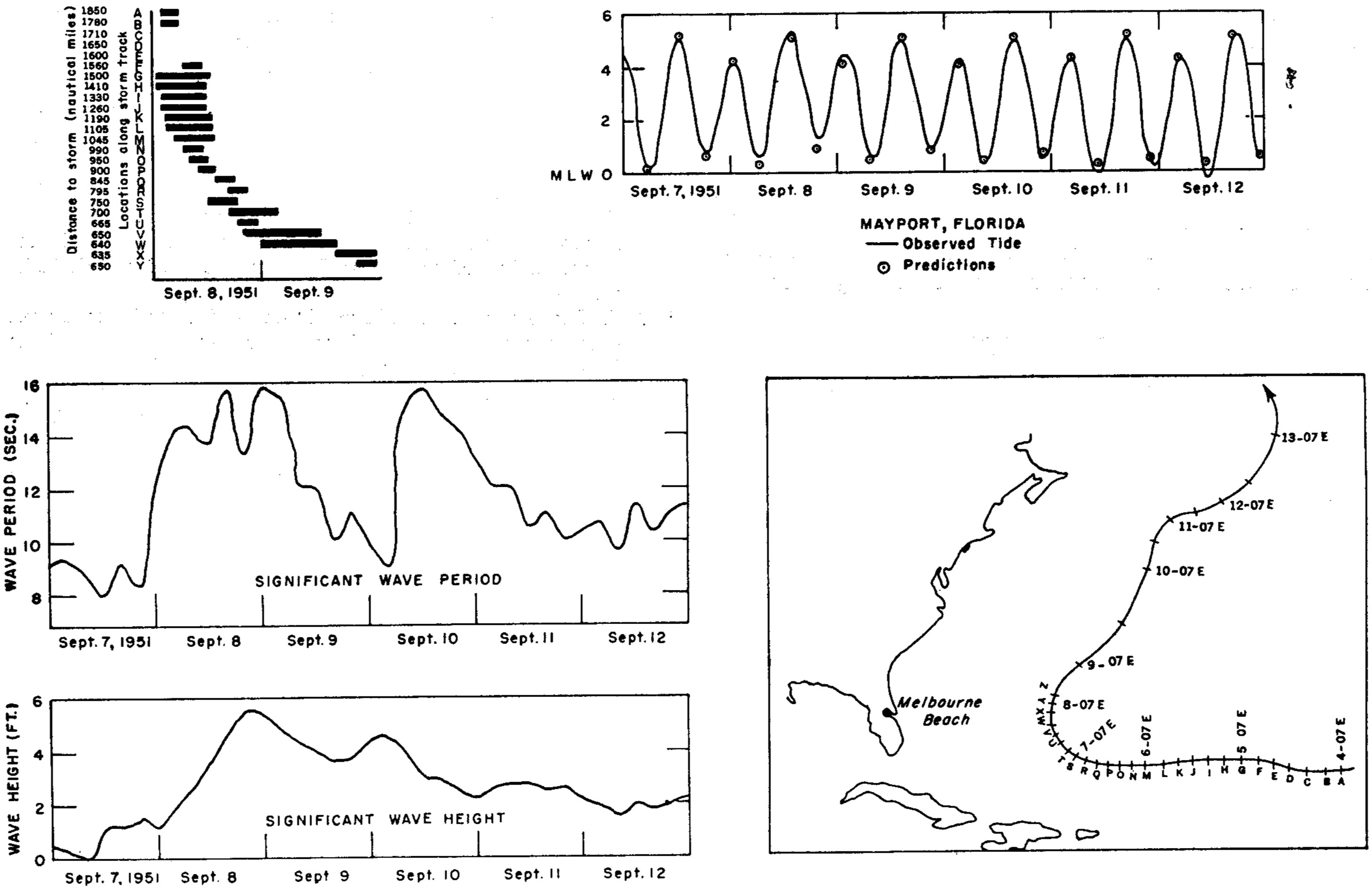

FIGURE 5.—Significant wave heights and periods recorded at Melbourne Beach, Fla., by the Beach Erosion Board during period of a hurricane of September 1951. The bar graph shows the possible locations of the storm that could account for the waves that were recorded at the various times indicated on the abscissa. A location was considered as possible when the wave velocity based on the recorded period agreed within one knot with the theoretical wave velocity based on group velocity and distance to the storm. For example, the waves recorded on September 9 at 2000 EST probably originated at location X along the storm path. Observed tide curve and predictions of high and low tide are for Mayport, Fla.

to be observed at a particular time. It seemed reasonable that, if the computed and observed wave velocities were within one knot of each other, the observed waves could have originated at the location being considered in that instance. Figure 5 includes the path of the September 1951 hurricane, the distance to the storm at 4-hour intervals, and the periods and heights of the significant waves. The bar graph shows the possible locations of the storm that could account for the waves that were recorded at the various times indicated on the abscissa. The locations of the storm center are indicated on the storm track by alphabetical symbols. Because 4-hour positions of the storm were considered in this graph, a 2-hour extension has been added to each end of the components of the bar graph. This makes no component less than 4 hours duration. Also the distance to the storm center locations are shown along the ordinate. This figure shows that the swell arriving at some periods originated at a location over a long stretch of the storm path, whereas at other times the waves must have originated at a location within a much shorter stretch of the storm path. Although swell of this type has been suggested as a cause of abnormally high water levels along a coast due to mass transport of water, the tide record for Mayport, Fla., included in figure 5, shows no abnormality during this period.

The tide records for the two storms discussed above indicate that swell arriving from hurricanes does not necessarily cause abnormally high tide levels. These data support the observations of Redfield and Miller [6] that the rise in water level ahead of a hurricane is dependent on the wind field into which the storm is advancing.

5. SUMMARY

The data suggest that the highest values of the wave heights from 60 to 480 miles from the storm center occur with about equal frequency in the two right quadrants. Also the wave conditions of mature hurricanes do not change materially from one day to the next. Comparison of wave and tide records indicates that swell propagating out in advance of hurricanes does not necessarily contribute to the rise in water level.

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